A 5-km long waterborne CVES survey on the Po River in the town of Turin: preliminary results

A 5-km long waterborne CVES survey on the Po river in the town of Turin: preliminary results.

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Introduction

The geological imaging and characterization of a riverbed is an essential starting point to determine thickness, lateral continuity and hydrogeological properties of the submerged deposits and to investigate the interconnecting relationship between surface water and groundwater. However, geological prospecting in water-covered areas could be very difficult, expensive and time-consuming with traditional survey techniques. Direct investigations (e.g. continuous core boring) are often neither cost effective nor reasonably quick and adequate in number to cover the whole water stream and to obtain a reliable correlation of data over a wide area. Geophysical methods can therefore be very useful to investigate sediments which are entirely located beneath a water-covered area. Among the available geophysical methods the use of non-seismic methods to study water-covered area is relatively recent (Sambuelli and Butler, 2009).
Focusing on the electrical techniques used for waterborne surveys, Continuous Vertical Electrical Soundings (CVES) using multichannel resistivity meters makes possible to simultaneously perform several resistivity measurements, in a fast and cost-effective way. CVES have been applied in water-covered areas for different purposes and using different electrode configurations a review of successful case histories can be found in Colombero et al. (2014). Even if many of the previous studies agree that the use of submerged electrodes allow better penetration in the submerged sediments, the use of floating electrodes seems sometimes preferable, since data acquisition is faster. With the floating cable arrangement, exponentially spaced electrodes appear to provide the best resolution with depth (Allen and Merrick, 2007).
We preliminary discuss the results of a continuous electrical resistivity survey carried out on the Po River, in a 5-km long urban sector of its flow across the City of Turin (NW Italy). The main objective of the study was to obtain a first assessment on the characterization of the riverbed sediments, in order to define nature, composition, geometry and spatial relationships of the detected bodies for further geological and hydrogeological reconstruction.

The geological context

In the urban area of the city of Turin, the Po River flows at the western edge of the SW-NE-elongated reliefs of the Turin Hill (Fig. 1). The morphology of the relief is remarkably asymmetric, with the presence of a relatively steep north-western slope and a much less inclined southern slope.

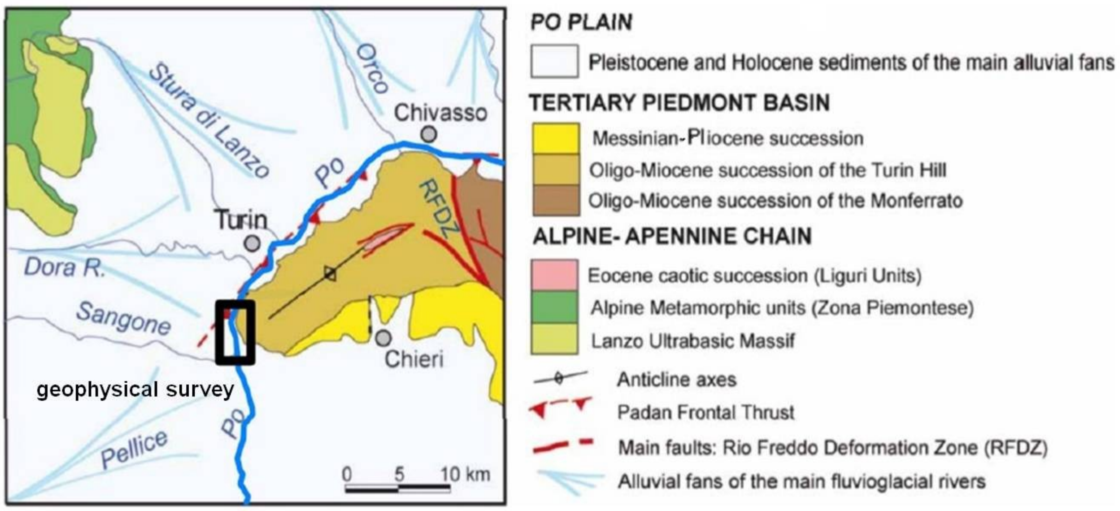

Figure 1. Structural geological model of Turin Hill and Po Plain in the area of Turin; the black bold square highlights the study area (modified from Forno and Lucchesi, 2015).

From a structural point of view, Turin Hill consists of a marine succession from the Upper Eocene and the Pliocene (Bortolami et al., 1969). This Tertiary sequence lies on a Southalpine metamorphic bedrock (Mosca, 2006). The whole sedimentary succession of Turin Hill is variously deformed, forming an asymmetrical anticline with a SW–NE-oriented axis. This NW verging structure overthrusts onto the Po Plain along the Padan Frontal Thrust currently buried by the Quaternary fluvial sediments of the Po Plain (Castellarin, 1994; Festa et al., 2009).
In particular, for the hillside next to the study area (NW side), the most superficial formation, belonging to the Oligocene-Miocene succession, is the Baldissero Unit (Synthem III Langhian). This Unit consists of marl and sandstones. Arenaceous-conglomeratic bodies with clasts of ophiolite, gneiss and quartzite are present at different levels. Its extension is about several kilometers and thickness varying between 50 and 350 m (eg. Colle Maddalena). Along the NW side of the Torino Hill, the Baldissero Unit is sometimes covered by deposits belonging to synthems of San Vito (Middle Pleistocene), Cavoretto (Upper Pleistocene) and Monte dei Cappuccini (Upper Pleistocene). These synthems are suspended stream terraces stored on N and NW slopes of the Torino Hill with thicknesses varying between 1 and 5 m and covered by aeolian deposits (Forno et al., 2002; Boano et al., 2004; Forno & Lucchesi, 2005). San Vito Synthem consists of sands, silts and weathered gravels and is located between 175 and 300 m above the current plain. Deposits belonging to Cavoretto Synthem consist of silt and sand weakly weathered and are located between 110 and 175 m above the plain. Monte dei Cappuccini Synthem consists of sand, silt and weakly weathered gravel and is located between 30 and 110 m above the plain. At the foot of the NW side of the Turin Hill, in the right bank of the Po River, extensive fluvial deposits of unknown thickness (Upper Pleistocene - Holocene) is found as a cover of Baldissero Unit. These are composed of gravel and fresh or slightly weathered sandy gravel covered across the board by a blanket of sand and silty sands of decimetric or metric thickness. Below this Quaternary covers, the sediments of Turin Hill are expected to continue at depth, progressively deepening towards NW.

The geophysical acquisition

A waterborne continuous electrical profile was acquired on the Po River, from the confluence of the Sangone River (south) to the very city centre of Turin (north, Murazzi del Po), for a total length of approximately 4850 m of acquisitions (Fig. 2).
The survey line passes throughout four bridges that represented difficult survey points both for the acquisition operations and for the strong electrical anomalies due to pier foundations. An array of nine electrodes fixed on a floating cable (96 m) dragged by a small boat was used for the survey. The array has two current electrodes, in the cable part closest to the boat, followed by eight potential electrodes. The current electrodes are 32 m apart, while the seven couples of potential electrodes had exponentially increasing spacing, from 0.5 m to 32 m. The first potential electrode was 0.5 m from the farthest current electrode. In the continuous profiling set up, dipole-dipole array data are collected measuring voltage potential differences between subsequent couples of potential electrodes given the same current injecting dipole. The towed cable floated on the river surface thanks to plastic floaters fixed near the electrodes that were fully submerged. The cable was kept stretched by a raft fixed at its end. We used a multichannel georesistivimeter (Syscal Pro in Sysmar upgrade – Iris Instruments) which was able to simultaneously acquire the seven potential measurements. The resistivity meter and the end of the cable were connected to a GPS device, in order to accurately record the spatial position of the acquired data. The acquisition step is about 2 seconds which results, on average, in one vertical electric sounding every 4 m. To recover the water depth, in order to constrain the data inversion, we connected to the IRIS georesistivimeter, and fixed to the side of the boat, a 170 kHz Airmar DT800 echo sounder. On average we had a bathymetry measure every 1 m.
We track the boat and the cable as in the following. Two different GNSS (Global Navigation Satellite Systems) instruments were used during the survey: the first one was a dual frequency multi-constellation receiver (Leica 1230+GNSS) that was installed on the main boat, while the second one was a single frequency cartographic receiver (Topcon GRS-1) installed on the raft in order to estimate the direction of the cable where all electrodes are settled. Both real-time and post-processing approaches were followed. The position of the boat was determined in real-time thanks to the Regione Piemonte CORSs (Continuous Operating Reference Stations) network, performing an NRTK (Network Real-Time Kinematic) positioning, obtaining an accuracy of solutions of about 2-4 cm.

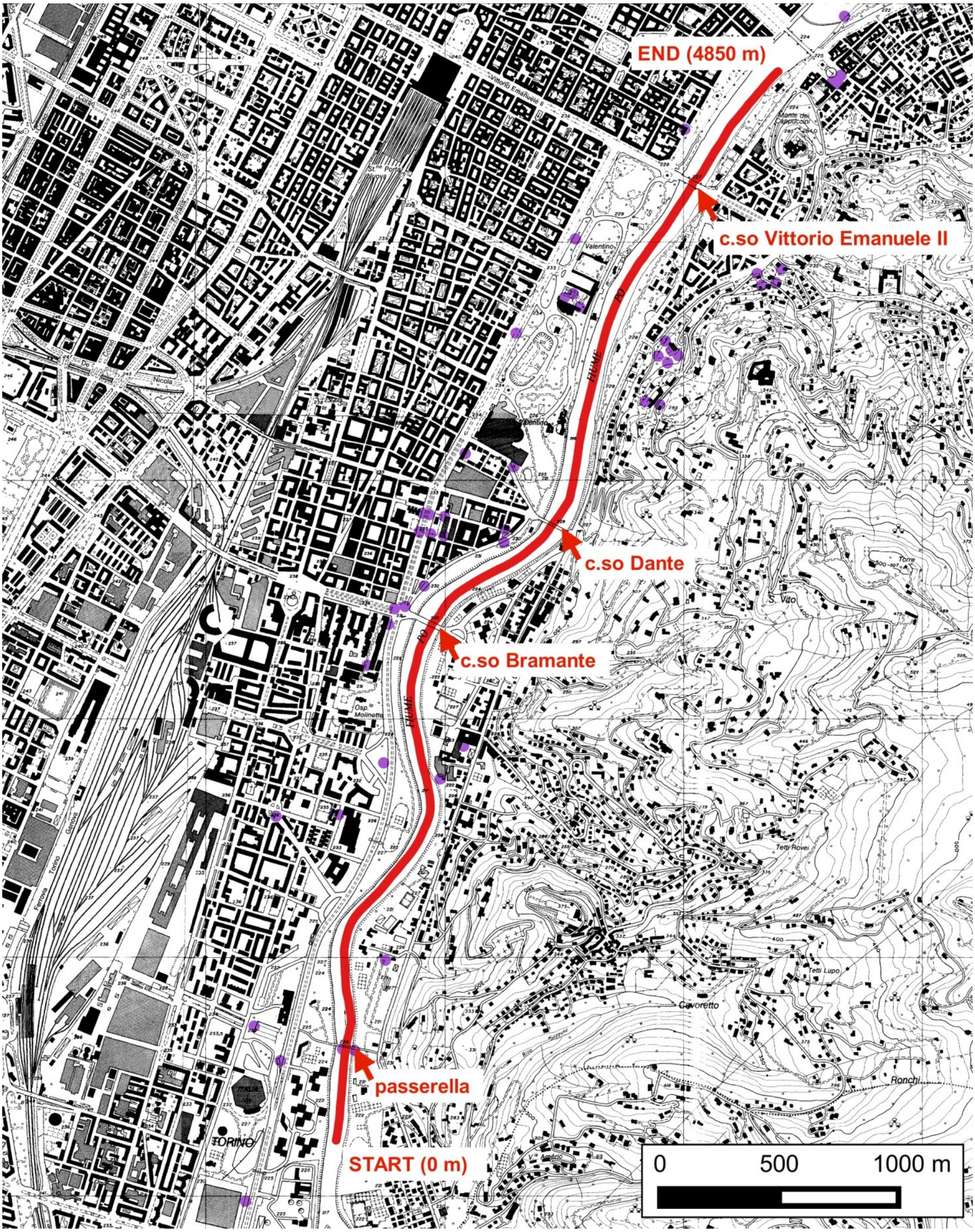

Figure 2. Survey line (in red) from the south to the north. Red arrows highlight the location of bridges. Purple dots refer to available geological logs and water wells with stratigraphic information.

As far as the raft is concerned, we acquired only the raw data that we post-processed in a single base solution (considering a master station 6 km far from the test-site), thanks to a commercial software, reaching a sub-centimeter accuracy. We considered only positions with fixed phase ambiguities in order to obtain the best accuracy available today with GNSS instruments, at the end of the process we obtained 2 highly accurate positions every second.

Data processing

Before the inversion a statistical analysis of the data was performed, in order to evaluate the homogeneity of water resistivity and data variability with depth. The first three potential dipoles with smallest reciprocal spacing mainly investigated the river water, which has a constant resistivity value of 43 Ω m over the whole travel path. On the other hand, the following four dipoles are expected to give information about the riverbed sediments.

CVES data were inverted using both a classical 2D tomographic processing and a laterally constrained inversion (LCI) approach. The LCI was developed to invert CVES data acquired along a profile by Auken and Christiansen (2004). This approach is based on a pseudo-2D layered parameterization of the investigated geological medium: the inversion result is a set of 1D consecutive resistivity models, each one corresponding to a sounding, composing a pseudo-2D section. All the VES soundings along a profile are inverted simultaneously by minimizing a common objective function, which contains all the acquired data, the available a-priori information and lateral constraints among consecutive models. Through the lateral constraints, information from one vertical electrical sounding are interconnected with the neighbouring ones, producing the final pseudo-2D section. The lateral constraints are chosen in a way to allow for pseudo-2D sections that are more or less homogeneous on the basis of the geological setting of the investigated area. In particular, the degree of lateral homogeneity of the considered model parameters is controlled by the strength of the constraints. If the expected lateral variability is small, a strong constraint will be applied; conversely if a large variation is expected, the strength of the constraint will be relaxed.

For a reliable inversion auxiliary a-priori data are also fundamental to ensure that as much known information as possible is considered in the inversion process. Crucial information for waterborne surveys includes bathymetry and water resistivity, which describe the properties of the water column. By providing these constraints, the inversion procedure is focused on the deposits beneath the riverbed, thus allowing a more accurate delineation of the sediment's electrical properties.

The conceptual reference model on which the inversion process was based is a three layered medium. For each inversion it was possible to a-priori fix the thickness and the resistivity of the water column (first layer). The first layer thickness was a-priori known thanks to echo sounder measurements of the bathymetry conducted simultaneously to the electrical survey. The first layer resistivity was kept constant (43 Ω m) considering the low variation of the mean of the nearest potential dipoles. No constraints were set for the second layer (fluvial deposits) while the electrical resistivity of the third layer (Turin Hill marls) was fixed to the value 23 ± 20 Ω m (mean and standard deviation of the whole raw measurements dataset for the seventh dipole) in order to force the inversion to find a lateral continuity for the deepest deposits. An appropriate Matlab code was developed to implement the inversion, similar to the one described in Colombero et al. (2014).

On the other hand, classical 2D inversion was carried out using Res2DInv software, in continuous resistivity profiling mode, fixing both the water resistivity and the bathymetry values (Loke M.H. and Lane J.W., 2004).

Preliminary results

In Fig.3 the results of the inversion of the whole dataset are shown, both for the LCI approach and for the classical 2D tomography. To maintain a readable vertical scale the profile has been split in 1km stretches.

The depth of the riverbed varies from a minimum of 2 m to a maximum of 10 m. Below the water layer (blanked in all the sections) a thick layer of sediments with resistivity higher than water resistivity (43 Ω m) is found. The layer thickness is not homogeneous, showing irregular depressions and reliefs, but generally it seems to progressively slightly increase towards north. Resistivity values range from the water value up to 250 Ω m. Quite low values are shown in the first 2400 m of the survey line (43-90 Ω m), from this point to the end of the survey the resistivity increases. This first layer of sediments is characterized by the fluvial deposits (mainly silt, sand and gravel) of the Po River. The increase in resistivity from south to north can be linked to a local increase in granulometric size of the sediments or to the presence of more compacted or cemented horizons.

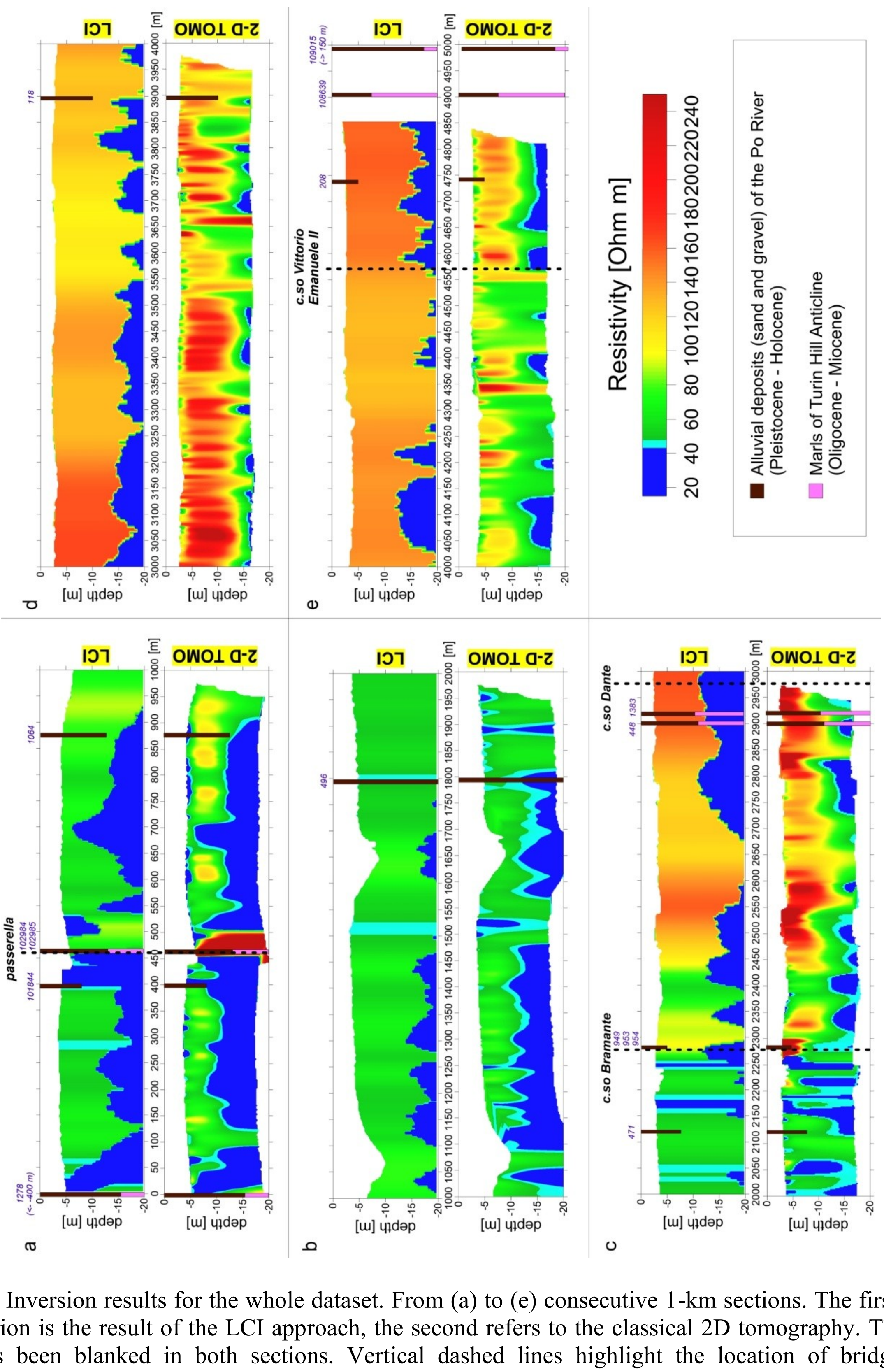

Figure 3. Inversion results for the whole dataset. From (a) to (e) consecutive 1-km sections. The first line of each section is the result of the LCI approach, the second refers to the classical 2D tomography. The water layer has been blanked in both sections. Vertical dashed lines highlight the location of bridges. The simplified geological information nearest to the river are plotted in direct comparison with the geophysical results.

Due to the three-layer model assumption, LCI results show for this horizon a unique mean value of around 150 Ω m in the last sections, while 2D tomography results distinguish an upper sub-layer with higher resistivity and a lower horizon with values comparable with the previous sections.

The bottom part of each section is instead characterized by sediments with resistivity values (20-40 Ω m) lower than water resistivity, that could be likely related to the marls of Turin Hill marine sequence. The morphology of this horizon is quite undulating, suggesting strong erosional phenomena both along the main flow of the river and at the confluence of the lateral tributary streams. The depth of the marls ranges from a few meters in the southern sections to more than 15 m toward north.
The geophysical results were compared with direct geological information, consisting of logs and water wells with stratigraphic information in the surroundings of the river banks. Unfortunately, not all the available direct surveys reached the marls, but where the investigation depth was higher, the data were found to be in good agreement (Fig. 3c). A strong electrical anomaly was detected near the first bridge of the survey, due to the pier foundation structure. These data were rejected for the LCI approach, but remained in the 2D tomographic results (Fig. 3a).

Conclusions

This research moved from one main question: how deep is the top of Miocene sediments below the Po River in the City of Turin? The answer would have implications in many fields: it would allow for a better knowledge of the structural geology of Turin Hill, a better understanding of the relationship between surface and groundwater and finally, being the top of Miocene a marly unit (the Baldissero Formation), an interesting indication, from a geotechnical point of view, for every engineering work across or below the river.
Many water wells, drilled in the town, even nearby the left bank of the Po River, did not find the top of the marls, and the depth of the Miocene could only be guessed by outcrops in the hill and some rare information from deeper logs. The asymmetry of the Turin Hill anticline, according to these preliminary results, has been validated for the Miocene, from geophysical data, along a 5-km section parallel to the anticline axis.
According to these preliminary results, the marls below the river are at depth ranging from 3 to 15 m. Only in some short stretches of the survey their depth exceeds the 20 m, a reasonable depth of investigation of CVES. These marls surely have different hydrogeological and geotechnical properties with respect to the Quaternary fluvial sediments. Marls will likely have cohesion and, even if they may have some secondary porosity due to tectonic fractures, a different hydraulic conductivity.
They are the impervious bedrock below the alluvial plane and therefore, in the Turin area, they represent the bottom of the shallowest aquifer that drains into the Po River.
Moreover, according to our preliminary results the depth of the top of the marls could occasionally intersect engineering works across or below the Po riverbed.
The information we obtained, still under process and interpretation, were gathered in a half a day campaign, involving roughly eight people and two boats. Even at this stage of work, considering that the full implication of our findings is still to be exploited, these results seems of interest and another survey along other 5 km of the Po River, to the north of the one presented, is going to be planned.

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